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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 4 : A61N 1/00

A1

(11) International Publication Number: WO 90/00912

(43) International Publication Date: 8 February 1990 (08.02.90)

(21) International Application Number: PCT/US89/03070

(22) International Filing Date: 14 July 1989 (14.07.89)

(30) Priority data: 222,882 22 July 1988 (22.07.88) US

(81) Designated States: AT (European patent), AU, BE (European patent), CH (European patent), DE (European patent), FR (European patent), GB (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent).

Published
With international search report.

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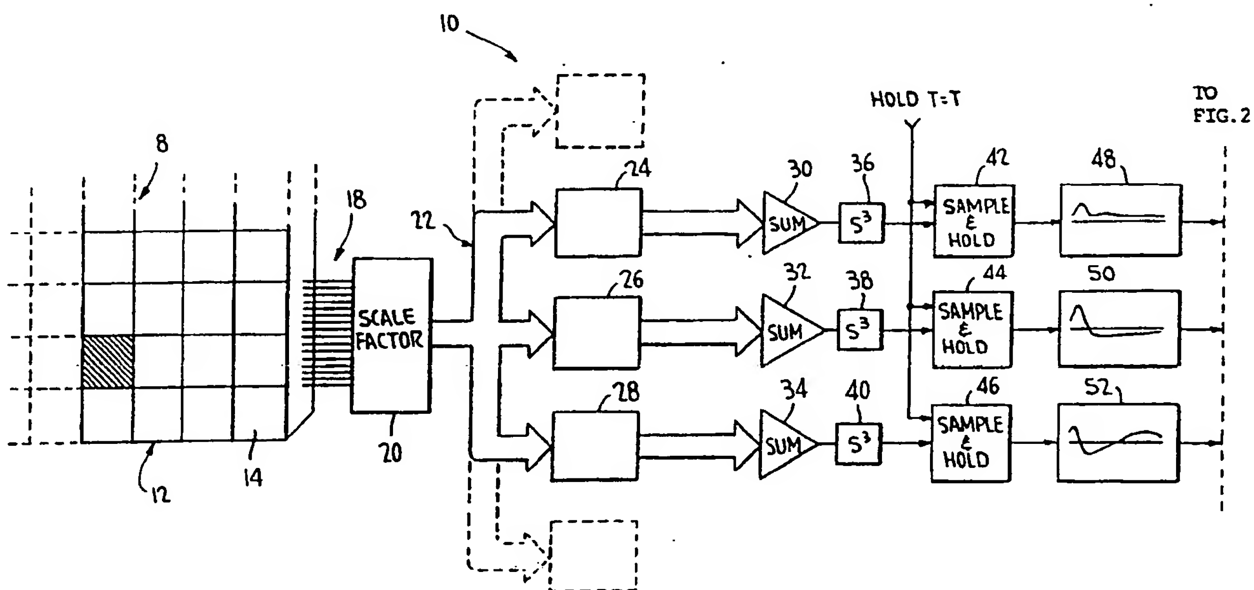
(54) Title: APPARATUS AND METHOD FOR TRANSMITTING PROSTHETIC INFORMATION TO THE BRAIN



(57) Abstract

An apparatus and method for transmitting prosthetic information to the brain contains an array of sensory elements (12) that receive energy from an external stimulus and process those signals via neural filters (24, 26 and 28) and neural waveforms to produce a pulse or "spike" train that is temporally encoded with information that is functionally related to the external stimulus. The simulated spike train, when applied to an appropriate area of the brain, produces perceptions that are functionally related to the sensed external stimuli so that a subject can discriminate between different spike trains representative of different external stimuli.

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APPARATUS AND METHOD FOR TRANSMITTING PROSTHETIC INFORMATION TO THE BRAIN

BACKGROUND OF THE INVENTION

The present invention relates to transmission of sensory information obtained by a prosthetic device to the brain to create a sensory perception. In particular, the present invention relates to the transmission of visual, audile, or tactile information to the brain in an encoded form that causes a functionally related perception on the part of the subject.

In normal circumstances, a healthy human being receives a stimulus from the external environment that is detected by the appropriate type of receptor. For example, photoreceptors within the eye detect light with each photoreceptor converting the received stimulus into neuron impulses. This conversion of the stimulus energy into neuron impulses takes place in one or more neurons that are associated with the receptor. Each neuron then emits a neuron spike sequence that is used by the brain to obtain sensory perception. The combination of many neurons, each transmitting many neuron spike trains provide a complete or global sensory perception.

It is known that a simulated neuron spike or pulse train can produce a sensory perception in a subject when applied to selected areas of the brain, spinal column, or nerves of a subject. Additionally, the brain has been 'mapped' so that specific locations on or within the brain are associated with specific sensory perceptions. Placement of an electrode at an appropriate location and stimulated with electrical pulses will produce a sensory perception. For example, an electrode placed on the striate cortex and to which a single simulation neuron impulse is transmitted will cause some type of visual

perception.

Repeated pulses to a specific location, such as the striate cortex, will produce some type of perceivable image. However, meaningful information as to form, luminescence, and color is not conveyed. It is presently believed that the informational content for all dimensions of a sense have their basis in a coding scheme that is based upon the number of neuron impulses that occur during a predetermined interval, for example, a greater number of neuron impulses are believed to be a function of a more intense perceived parameter. However, this coding scheme only allows one dimension of a sense to be coded by each neuron. Proponents of this coding scheme believe that the large number of neurons contain a distribution among them that allows the various dimensions of sense to be recognized so that perception can take place. However, it has not been possible to determine how these various dimensions are recognized using this population coding scheme. It has not been possible to develop a prosthetic device using this population coding principle which can sense an external stimulus and transmit information to the brain so that meaningful sensory perception can take place.

SUMMARY OF THE INVENTION

In view of the above, it is an object of the present invention, among others, to provide an apparatus and method for transmitting prosthetic information to the brain.

It is another object of the present invention to provide an apparatus and method that will allow meaningful encoding of visual, audile, or tactile sensory information.

It is still another object of the present invention to provide an apparatus and method to produce simulated

neural impulses that replicate the neural impulses produced naturally by neurons in the body.

In view of these objects, and others, the present invention provides an apparatus and method for transmitting prosthetic information to the brain in the form of simulated neuron impulses that contain a time varying component. This time varying component corresponds to the time varying component that exists during consecutive neuron impulses in an individual neuron and allows information concerning multiple dimensions of a sense to be contained in the simulated neuron impulse train.

The apparatus and method of the present invention sense an external stimulus with an array of sensors. The output of each of these sensors is used to determine simulated neuron impulses associated with each sensor. Each sensor acts as a channel that sends its simulated neuron impulses to the appropriate sensory location so that the sense can be perceived. The array of channels transmits simulated neuron impulses in parallel to allow sensory perception.

The present invention utilizes a series of characteristic sensory functions in combination with respective temporal neural filters. Processing of sensory perceived parameters via these characteristic functions and neural filters results in simulated neural impulses, or a spike train, containing the properly time varying components that allow the brain to sense the external stimulus.

The present invention advantageously allows a person to perceive environmental parameters, such as light, sound, or touch, via simulated neural spike trains that emulate naturally occurring spike trains with a temporal modulation scheme in such a way that the perception based

on the simulated spike train will be functionally related to the external stimuli or parameter.

Other objects and further scope of applicability of the present invention will become apparent from the detailed description to follow, taken in conjunction with the accompanying drawings, in which like parts are designated by like reference characters.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a partial schematic block diagram of a system for generating a simulated neural impulse for stimulating the visual cortex of the human brain;

FIG. 2 is a partial schematic block diagram of the system of the present invention;

FIG. 3 is a legend indicating the manner by which FIGS. 1 and 2 are to be read;

FIG. 4 is a graphical illustration of a first neural transform in which the abscissa represents time and the ordinate represents magnitude;

FIG. 5 is a table providing quantitative data as to the neural transform of FIG. 4 in which the left column represents time in milliseconds from zero to 315 ms. and the right column presents the corresponding magnitude value;

FIG. 6 is a graphical illustration of a second neural transform in which the abscissa represents time and the ordinate represents magnitude;

FIG. 7 is a table providing quantitative data as to the neural transform of FIG. 6 in which the left column represents time in milliseconds from zero to 315 ms. and the right column presents the corresponding magnitude value;

FIG. 8 is a graphical illustration of a third neural transform in which the abscissa represents time and the ordinate represents magnitude;

FIG. 9 is a table providing quantitative data as to the neural transform of FIG. 8 in which the left column represents time in milliseconds from zero to 315 ms. and the right column presents the corresponding magnitude value;

FIG. 10 is a schematic block diagram of a stored-program controlled processor for effecting various transformations in a digital manner;

FIG. 11 is a flow diagram illustrating a control sequence for converting digital values into a temporally modulated spike train suitable for stimulating the striate cortex to effect a visual perception in a subject;

FIG. 12 is an illustration of an image pattern, its corresponding temporal encoding, and its corresponding temporally modulated spike train suitable for stimulating the visual cortex to provide a perception that is a function of the image pattern; and

FIG. 13 is an illustration of another image pattern, its corresponding temporal encoding, and its corresponding temporally modulated spike train suitable for stimulating the visual cortex to provide a perception that is a function of the image pattern.

DESCRIPTION OF THE PREFERRED EMBODIMENT

An exemplary system in accordance with the present invention for generating simulated neural impulses from an environmental parameter and providing a functionally related 'spike' train for stimulating the brain to effect a functionally related perception of the environmental parameter is shown in FIGS. 1 and 2 and is designated generally therein by the reference character 10. The system 10 is designed to sense an environmental parameter in the form of variations in light that define an image and provide a corresponding spike train that is

temporally modulated, i.e., pulse position modulated, and which, when used to stimulate a portion of the brain of a subject, produces a perception that is functionally related to the sensed light or image. As shown in FIG. 1, the exemplary embodiment of the system 10 includes an array 8 of individual photoreceptors 14. In FIG. 1, sixteen photoreceptors 14 are shown in solid-line illustration and represent an input sub-array 12 for one sub-image information channel for transducing environmental light into corresponding electrical signals presented on respective output lines, indicated generally at 18. As can be appreciated, other photoreceptors 14 are similarly arrayed as the input transducers for other sub-image information channels (not specifically shown in FIGS. 1 and 2) so that a multi-channel system is provided to effectively assemble a set of output spike trains that are representative of the image sensed by the array 12. The photoreceptors 14 can be individual planar photocells, photodiodes, or phototransistors arranged in an array or can take the form of a subset of the photoreceptors on a planar integrated device. If desired, an optical system can be provided to image subjects of principal and secondary interest within a selected field of view onto the array 12.

A scale-factor conditioner 20 is provided to accept the outputs of the array 12 and introduce a scaling factor that is a function of the light-to-signal input/output function of the particular photoreceptors 14. The scaling factors are determined empirically and vary, for example, as a function of the sensitivity and spectral response of the particular photoreceptors 14. In addition, the scale-factor conditioner 20 can introduce a logarithmic function (typically $\log_e$) to compensate for the functional response characteristics of

the photoreceptors 14. Where the array 12 is part of a scanning camera, for example, the camera typically provides the logarithmic function compensation.

The appropriately scaled output of the scale-factor conditioner 20 is provided via an appropriate bus 22 connection to each of three signal-weighting filters 24, 26, and 28. Each of the signal-weighting filters accepts all the scale-factored signal outputs of the scale-factor conditioner 20 and multiplies the respective outputs by a specific weighting value to provide a spatial filter effect that is related to respective neural transforms described more fully below. For the sixteen signal lines of the input sub-array 12, weight values for the signal-weighting filters 24, 26, and 28 for the preferred embodiment are as listed, respectively, in Tables I, II, and III below and presented in the four-by-four array format corresponding to the input sub-array 12.

Table I

-0.423000	-0.004000	-0.118000	-0.099000
-0.329000	3.366000	0.888000	-0.285000
0.343000	8.327000	1.527000	-0.297000
-0.287000	-0.706000	-0.210000	-0.474000

Table II

-0.028300	-0.139600	-0.029400	-0.178400
-0.377900	-0.725700	-0.243300	0.083600
-0.273900	1.861400	-0.184400	-0.168000
-0.156200	-0.367900	-0.218200	-0.185200

Table III

-0.028640	0.128490	0.155270	-0.033330
0.108840	0.159940	0.183120	0.350690
-0.081850	0.212080	0.082500	-0.007050
-0.066830	-0.180620	-0.005260	0.068260

After the signal weighting is effected by the signal-weighting filters 24, 26, and 28, the respective outputs

are provided to summing amplifiers 30, 32, and 34, which sum the individual weighted inputs to provide a single respective scalar output S that is provided to respective cubic function (i.e., $S^3 = as^3+bs^2+cS+d$) generators 36, 38, and 40 that scale each signal in a non-linear manner to compensate for low input signal values. The summing amplifiers can be fabricated from conventional operational amplifiers configured in a summing mode, and the cubic function generators 36, 38, and 40 can be fabricated from conventional analog multiplier devices.

Sample-and-hold circuits 42, 44, and 46 are provided respectively at the outputs of the cube function generators 36, 38, and 40 and are designed to continuously sample the output voltage values. The system 10 is designed to generate output simulated neural impulses on a frame-by-frame basis, with the simulated neural impulses generated subsequent to each frame and prior to the subsequent frame. A frame is terminated on a system-wide basis by a timing signal $T=T_f$ which, when applied to the sample-and-hold circuits 42, 44, and 46, causes the respective circuit to store the signal value at its input for subsequent processsing as explained below. Each sample-and-hold circuit 42, 44, 46 can be defined by a series-connected capacitor and switch, such as a MOSFET.

Neural transform function units 48, 50, and 52 are provided, respectively, at the outputs of the sample-and-hold circuits 42, 44, and 46. Each neural transform function unit 48, 50, and 52 includes an empirically determined, time-dependent neural transfer function that is multiplied by the value stored in the respective sample-and-hold circuits 42, 44, and 46. The transforms are determined by measuring biological neuron responses to mathematically complete sets of stimuli, e.g., Walsh

patterns. It has been empirically determined that the transfer functions presented in neural transform function units 48, 50, and 52 are a statistically valid analog of actual neural responses. These waveforms, along with the corresponding three signal-weighting filters 24, 26, and 28, thus allow the system 10 to generate simulated neural impulses for use in stimulating the visual cortex of the brain.

The neural waveform for the neural waveform unit 48 is reproduced on an enlarged scale in FIG. 4 in which the abscissa represents time, and the ordinate represents magnitude. The neural waveform of FIG. 4 is also presented in a quantitative manner in FIG. 5 with the left column representing time in milliseconds between zero and 315 ms. and the right column representing the corresponding magnitude. In a similar manner, the neural waveform of neural waveform units 50 and 52 are shown in enlarged scale in FIGS. 6 and 8, respectively, and their quantitative data in FIGS. 7 and 9. While 64 time and corresponding data values are shown in FIGS. 5, 7, and 9, it is preferred that data values at one millisecond intervals be utilized in the signal processing, these values provided by interpolation of the data values presented in FIGS. 5, 7, and 9.

Further disclosure regarding the neural waveforms and the neuro-physiology of the present invention is provided in the following publications, the disclosures of which are incorporated herein by reference: Richmond, B. J., L. M. Optican, M. Podell, and H. Spitzer (Jan., 1987) "Temporal encoding of two-dimensional patterns by single units in primate inferior temporal cortex; I. Response characteristics." J. Neurophysiol. vol. 57:132-146; Richmond, B. J. and L. M. Optican (Jan., 1987) "Temporal encoding of two-dimensional patterns by single units in

primate inferior temporal cortex; II. Quantification of response waveform." J. Neurophysiol. vol. 57:147-161; Optican, L. M. and B. J. Richmond (Jan., 1987) "Temporal encoding of two-dimensional patterns by single units in primate inferior temporal cortex. III. Information theoretic analysis." J. Neurophysiol. vol. 57:162-178; Richmond, B. J. and L. M. Optican (1986) "Temporal encoding of pictures by striate neuronal spike trains. I. The multiplex-filter hypothesis." Society for Neuroscience, Abstract 12:431; Optican, L. M. and B. J. Richmond (1986) "Temporal encoding of pictures by striate neuronal spike trains. II. Predicting complex cell responses." Society for Neuroscience, Abstract 12:431.

Once the time-dependent neural transfer functions in the neural waveform function units 48, 50, and 52 are multiplied by the values stored in the respective sample-and-hold circuits 42, 44, and 46. The products are summed in a summing amplifier 54 to provide a time-varying output that is related to the image sensed by the input sub-array 12. The output of the summing amplifier 54 is provided to an analog-to-digital converter 56 to provide a digitized output thereof for subsequent conversion into a spike train as explained more fully below.

The neural waveform units 48, 50, and 52 are shown in functional block form in FIGS. 1 and 2 and are preferably implemented in a digital manner with a stored-program controlled processor. For example and as shown in FIG. 10, the functions performed by the neural waveform units 48, 50, and 52 and the summing amplifier 54 are performed by a microprocessor 100 that is coupled to a read-only-memory (ROM) 102 and a random-access-memory (RAM) 104. A multiplexer 106 accepts the inputs from the sample-and-hold circuits 42, 44, and 46 and, in response to

appropriate 'select' signals, provides the selected sample-and-hold value to an analog-to-digital (A/D) coverter 108 which, in turn provides the corresponding digitized sample-and-hold value to the microprocessor 100. A clock 110 provides the necessary timing and control signals to the various devices to effect synchronized operation.

The ROM 102 includes the data tables of FIGS. 5, 7, and 9. The clock 110 provides the timing and control signal to the multiplexer 106 to select one of the sample-and-hold values which is digitized and stored in one of the general purpose registers in the microprocessor 100 with the procedure repeated until three digital values representative of the three sample-and-hold values are stored in digital form. The microprocessor 100 then reads the first time value (i.e., t=0 ms.) from the ROM 102 for a first of the neural waveforms and effects a multiplication by the corresponding digitized value in sample-and-hold 42 and stores the respective product temporarily in the RAM 104. In a similar manner, the first values for the second and the successive neural waveforms are obtained from the ROM 102, multiplied by their corresponding value from their respective sample-and-hold circuits, and the products stored. The three products are then digitally summed and the results again stored. The second time value for the various neural waveforms are then obtained, multiplied by their respective digital sample-and-hold values, and the sum thereof stored in the RAM 104. As can be appreciated, the process is repeated in a recurring manner until a set of output values is obtained that corresponds to the output of the analog-to-digital converter 56 of the functional block diagram of FIGS. 1 and 2. Hence, FIG. 10 provides a circuit that implements

functional blocks 48, 50, 52, 54, and 56 of FIGS. 1 and 2.

Once the neural waveforms are multiplied by their respective sample-and-hold values and the products summed and digitized, as shown in functional form in FIGS. 1 and 2 or by the processor-implementated form in FIG. 10, the digital output is converted to a spike train the spacing of which encodes information functionally related to that sensed by the input sub-array 12. As shown in FIG. 2, the digital output of the analog-to-digital converter 56, which represents a succession of digital values representative of the processed neural waveform values, is presented to a stored-program controlled microprocessor 58 that is coupled to read-only-memory (ROM) 60 that contains a program sequence, as presented in FIG. 11, and a random-access-memory (RAM) 62 for storing various intermediate and other values. A clock 64 provides timing pulses while a controller 66 provides the necessary select, enable, and control signals to provide synchronous operation of the various devices. The microprocessor 58 is coupled, along with appropriate control lines, to a counter 68 that is periodically parallel-loaded with a preset threshold value X from a register 70. The output of the counter 68 is provided to a one-shot monostable multi-vibrator 72 that provides, in response to an appropriate trigger signal, a pulse or spike of selected pulse amplitude and duration. As explained below, a succession of such spikes are provided with an inter-spike temporal spacing that contains the encoded information from the image sensed by the input sub-array 12. The output of the one-shot 72 is provided through a conditioning amplifier 74 which controls the voltage output to provide a spike train of appropriate voltage level (typically 10 to 500 microvolts with a 50

to 100 microsecond spike width duration) for stimulating the appropriate spot or area of the visual cortex.

The microprocessor 58 of FIG. 2 operates in accordance with the control sequence of FIG. 11 to produce a temporally modulated spike train as a function of the digital values presented from the analog-to-digital converter 56. As shown in FIG. 11, the system initializes, in part, by storing 1 to the data pointer variable, N, with N having a maximum value N_{max} that represents the total number of digital data values for that frame and which must be converted into a spike train representative of that frame. For example, a frame can be represented by N_{max} = 300 digital values determined by interpolation of the 64 times values shown in FIGS. 5, 7, and 9, each value of which is the sum of the products of the corresponding values of the neural waveforms (FIGS., 4-9) and the sample-and-hold values.

After initialization, the one-shot 72 is triggered to provide an initial spike, have a pulse duration or spike width of between 50 and 100 microseconds and a selected voltage amplitude. A query is presented to determine if all the digital data values for a frame have been processed, i.e., if $N = N_{max}$, and, if so, the control returns to re-initialize for the next frame. If less than all the digital data values have been processed, the N^{th} digital data value is added to the contents of the counter 68. A query is presented to determine if the accumulated contents of the counter 68 are greater than a selected value X (i.e., 1000), and, if not, the data pointer N is incremented by 1 and the program loops to add the next data value to the counter 68, provided that N is not equal to N_{max}. If the counter sum is greater that X, the counter is decremented by X by effecting a parallel load from the register 70, and, substantially

concurrently, triggering the one-shot 72 to produce the next successive spike. Thereafter, the data pointer N is incremented by one with the program looping to continue to successively add the digital data values to the counter 68, decrement by X when X is exceeded, and issue the next successive spike. As can be appreciated, the time duration between each spike is a function of the rate at which the digital value accumulates to exceed X so that a temporally modulated spike train is generated, i.e., a spike train in which the inter-spike timing is varied as a function of the products of the corresponding values of the neural waveforms (FIGS. 4-9) with the sample-and-hold values that are a function of the image sensed by the input sub-array 12.

The spike train output of the one-shot 72 is provided to an amplifier 74 which provides a buffered output, typically no more than 10 - 100 microvolts, that is provided to a neural probe that is placed in a selected location on an appropriately mapped visual cortex of the brain of a subject to stimulate a neuron(s) to cause perception of an image or light pattern that is functionally related to that sensed by the input sub-array 12. The other adjacent channels (not specifically shown in FIGS. 1 and 2) similarly drive other neural electrodes place in an electrode grid pattern corresponding to the visual maps of the entire input array 8.

Exemplary temporally modulated spike trains, their corresponding waveforms, and the corresponding Walsh patterns are shown in FIGS., 12 and 13, and, as shown, the inter-spike spacing and the rate of changes thereof varies as a function of the waveform to produce a temporally modulated spike train. In practice, it has been found that inter-spike spacing varies between one

and 300 milliseconds.

The present invention has been disclosed as useful in providing a simulated spike train responsive to a sensed optical image; as can be appreciated, a different input sensor, such as an array of sound-responsive devices or pressure responsive devices can likewise be utilized to provide a simulated spike train responsive to a sensed sound or pressure. The present invention advantageously allows a person to perceive environmental parameters via temporally modulated simulated neural spike trains that emulate naturally occurring spike trains in such a way that a perception based on the simulated spike train will be functionally related to the external stimuli or parameter.

As will be apparent to those skilled in the art, various changes and modifications may be made to the illustrated apparatus and method for transmitting prosthetic information to the brain of the present invention without departing from the spirit and scope of the invention as determined in the appended claims and their legal equivalent.

What is claimed is:

1. An apparatus for transmitting prosthetic information about an external stimulus to the brain comprising:

means for sensing said external stimulus;

means for converting said sensed external stimulus into simulated neuron impulses that can contain information about multiple dimensions of said sensed external stimulus due to the presence of a time varying component in said simulated neuron signals; and

means for transmitting said simulated neuron impulses to the brain.

2. A method for transmitting prosthetic information about an external stimulus to the brain comprising the steps of:

sensing said external stimulus;

converting said sensed external stimulus into simulated neuron impulses that can contain information about multiple dimensions of said sensed external stimulus due to the presence of a time varying component in said simulated neuron signals; and

transmitting said simulated neuron impulses to the brain.

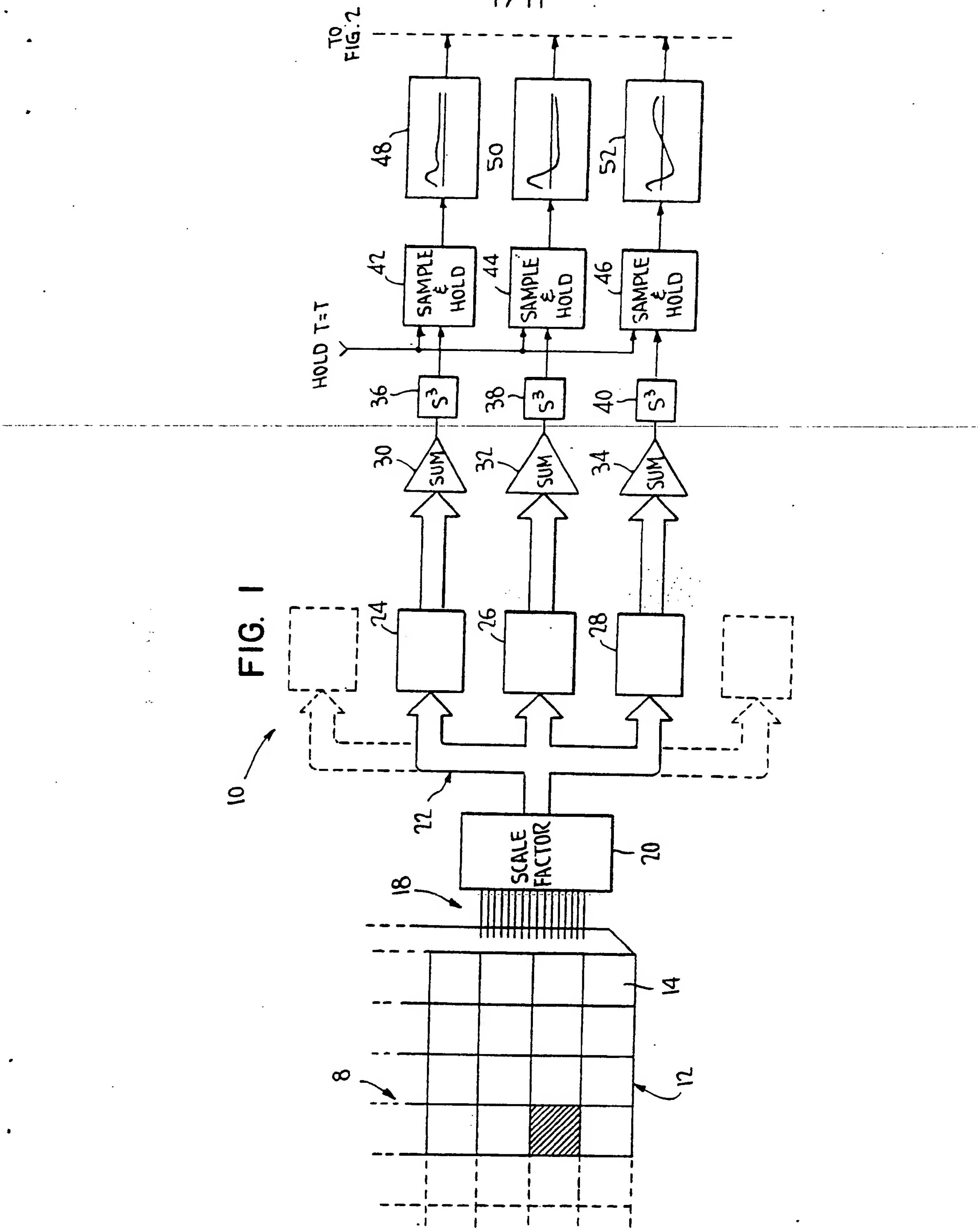
TO FIG. 2
48
50
52
42
SAMPLE & HOLD
44
SAMPLE & HOLD
46
SAMPLE & HOLD
HOLD T=T
36
S3
38
S3
40
S3
30
SUM
32
SUM
34
SUM
24
26
28
10
22
SCALE FACTOR
20
18
14
8
12

FIG. 1

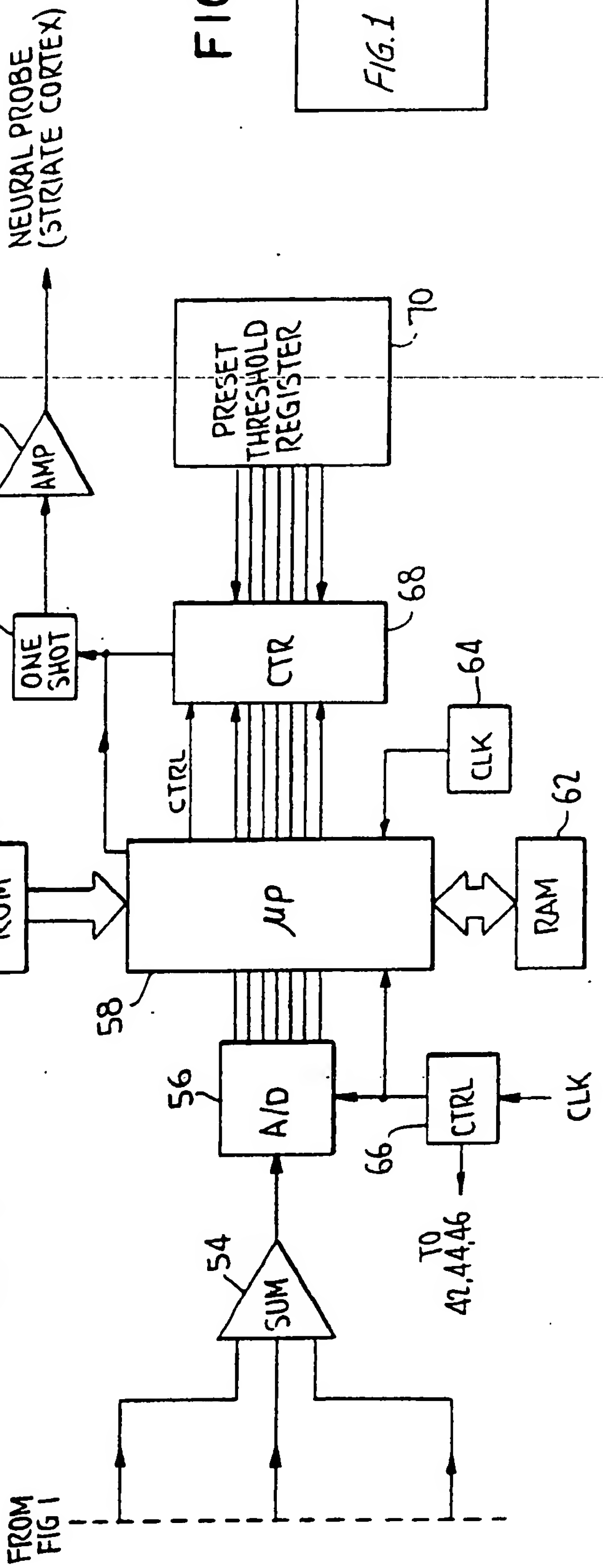

FIG. 2

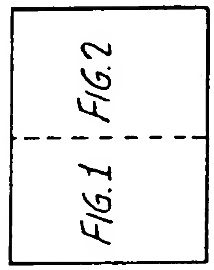

FIG. 3

FIG. 4

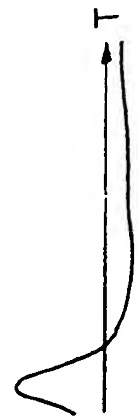

FIG. 6

FIG. 8

FIG. 5-1

TIME (ms)	VALUE
0	0.0443110
5	0.0753230
10	0.1170940
15	0.1632160
20	0.2041640
25	0.2312780
30	0.2403380
35	0.2327660
40	0.2138700
45	0.1901990
50	0.1671190
55	0.1478710
60	0.1337540
65	0.1247830
70	0.1202900
75	0.1192430
80	0.1204720
85	0.1226630
90	0.1247080
95	0.1259050
100	0.1261860
105	0.1257600
110	0.1248300
115	0.1233810
120	0.1214200
125	0.1191800
130	0.1170440
135	0.1153290
140	0.1138810
145	0.1122680
150	0.1103080

155	0.1082660
160	0.1064810
165	0.1049240
170	0.1032050
175	0.1010860
180	0.0987560
185	0.0966750
190	0.0951690
195	0.0942760
200	0.0937720
205	0.0933940
210	0.0929080
215	0.0921320
220	0.0910240
225	0.0896700
230	0.0882570
235	0.0870030
240	0.0860130
245	0.0851340
250	0.0841740
255	0.0830530
260	0.0819270
265	0.0809990
270	0.0803430
275	0.0798240
280	0.0793820
285	0.0790450
290	0.0787980
295	0.0783580
300	0.0772410
305	0.0751700
310	0.0722010
315	0.0687870

FIG. 5-2

FIG. 7-1

TIME (ms)	VALUE
0	0.0834020
5	0.1409390
10	0.2076300
15	0.2662960
20	0.2995730
25	0.2982760
30	0.2648230
35	0.2102740
40	0.1482040
45	0.0894680
50	0.0403130
55	0.0027080
60	-0.0240520
65	-0.0417880
70	-0.0525610
75	-0.0584730
80	-0.0616610
85	-0.0640590
90	-0.0670390
95	-0.0707800
100	-0.0747410
105	-0.0783210
110	-0.0813300
115	-0.0838470
120	-0.0857630
125	-0.0867970
130	-0.0869870
135	-0.0868480
140	-0.0868450
145	-0.0868750
150	-0.0863130

155	-0.0847000
160	-0.0822130
165	-0.0794450
170	-0.0770480
175	-0.0755010
180	-0.0751240
185	-0.0759200
190	-0.0775990
195	-0.0795150
200	-0.0809070
205	-0.0811940
210	-0.0802140
215	-0.0784800
220	-0.0768480
225	-0.0760120
230	-0.0758960
235	-0.0758870
240	-0.0753500
245	-0.0741620
250	-0.0727020
255	-0.0714120
260	-0.0705010
265	-0.0696150
270	-0.0681390
275	-0.0656960
280	-0.0626150
285	-0.0597700
290	-0.0579760
295	-0.0572640
300	-0.0568420
305	-0.0557990
310	-0.0535720
315	-0.0502330

FIG. 7-2

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FIG. 9-1

TIME (ms)	VALUE
0	0.0994760
5	0.1402630
10	0.1676830
15	0.1638380
20	0.1216490
25	0.0499750
30	-0.0311940
35	-0.1011310
40	-0.1475100
45	-0.1690590
50	-0.1718990
55	-0.1640830
60	-0.1516910
65	-0.1381650
70	-0.1257560
75	-0.1158630
80	-0.1086250
85	-0.1027740
90	-0.0964920
95	-0.0887020
100	-0.0794260
105	-0.0693570
110	-0.0593190
115	-0.0501140
120	-0.0420100
125	-0.0344360
130	-0.0264240
135	-0.0176150
140	-0.0085510
145	0.0004030
150	0.0095770
155	0.0194610

160	0.0297030
165	0.0390350
170	0.0463420
175	0.0515310
180	0.0555400
185	0.0594000
190	0.0637840
195	0.0689570
200	0.0749680
205	0.0814380
210	0.0875220
215	0.0922280
220	0.0950710
225	0.0963460
230	0.0969210
235	0.0978230
240	0.0995210
245	0.1018150
250	0.1041270
255	0.1061120
260	0.1078720
265	0.1095030
270	0.1107770
275	0.1113810
280	0.1112050
285	0.1103960
290	0.1089000
295	0.1062970
300	0.1019720
305	0.0957650
310	0.0881450
315	0.0800220

FIG. 9-2

FIG. 10

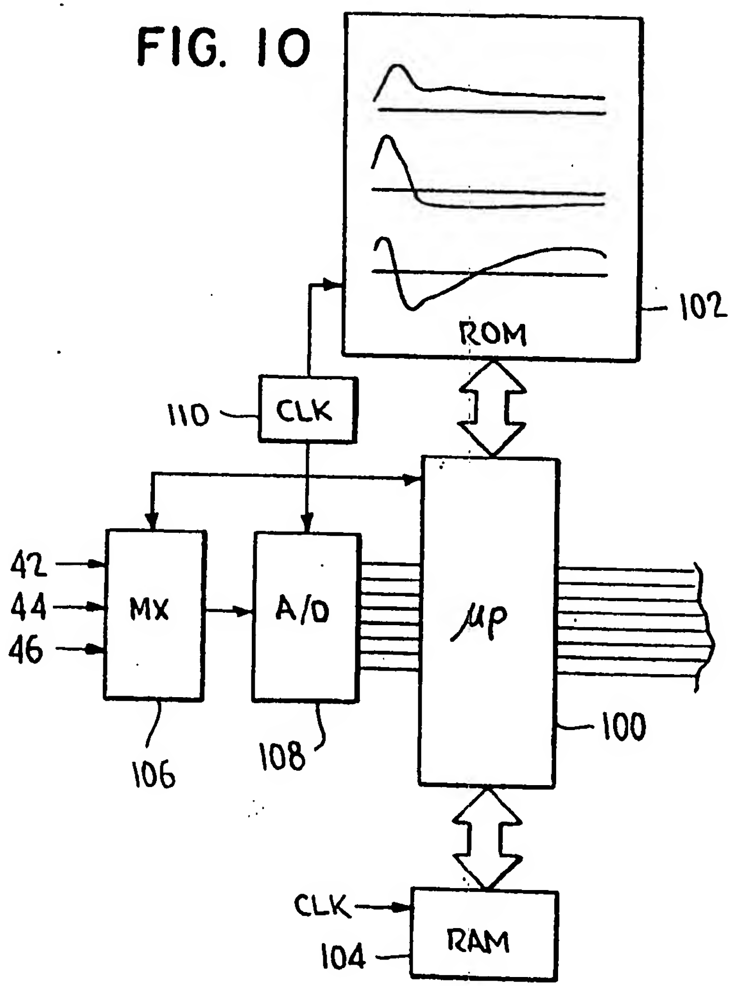
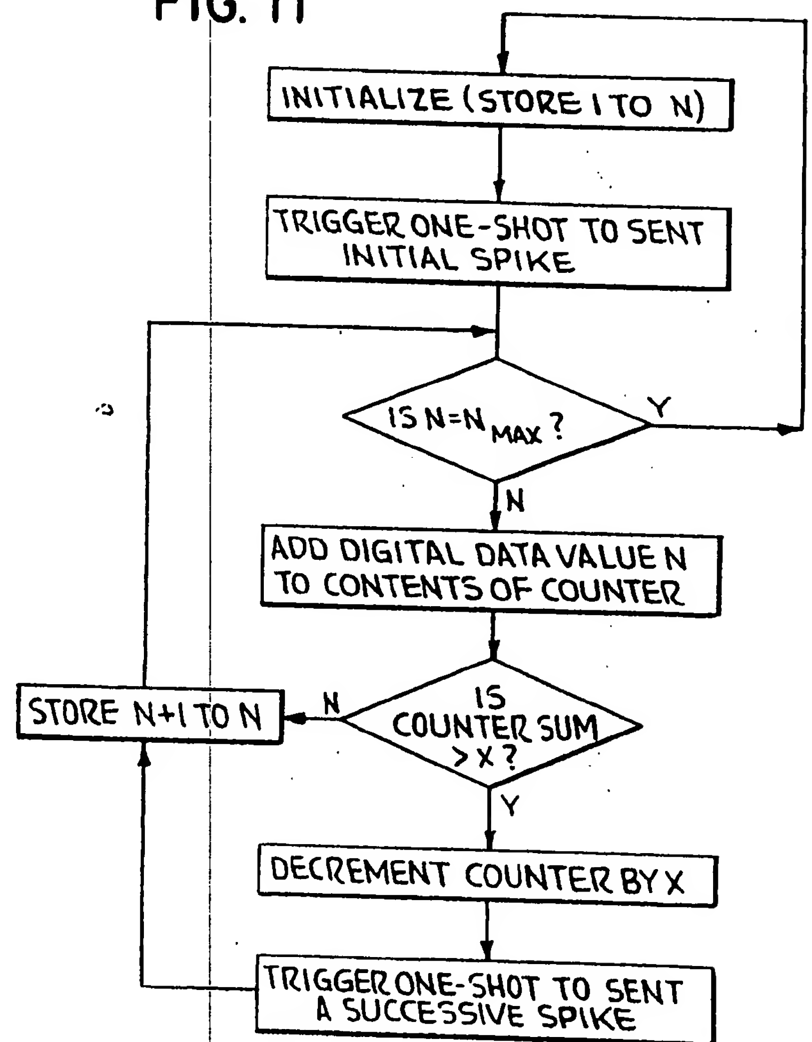
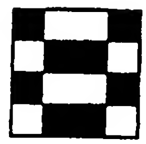

ROM
102
CLK
110
MX
A/D
μP
42
44
46
106
108
100
CLK
RAM
104

FIG. 11


INITIALIZE (STORE 1 TO N)
TRIGGER ONE-SHOT TO SENT INITIAL SPIKE
IS N=N MAX ?
Y
N
ADD DIGITAL DATA VALUE N TO CONTENTS OF COUNTER
IS COUNTER SUM > X ?
N
STORE N+1 TO N
Y
DECREMENT COUNTER BY X
TRIGGER ONE-SHOT TO SENT A SUCCESSIVE SPIKE



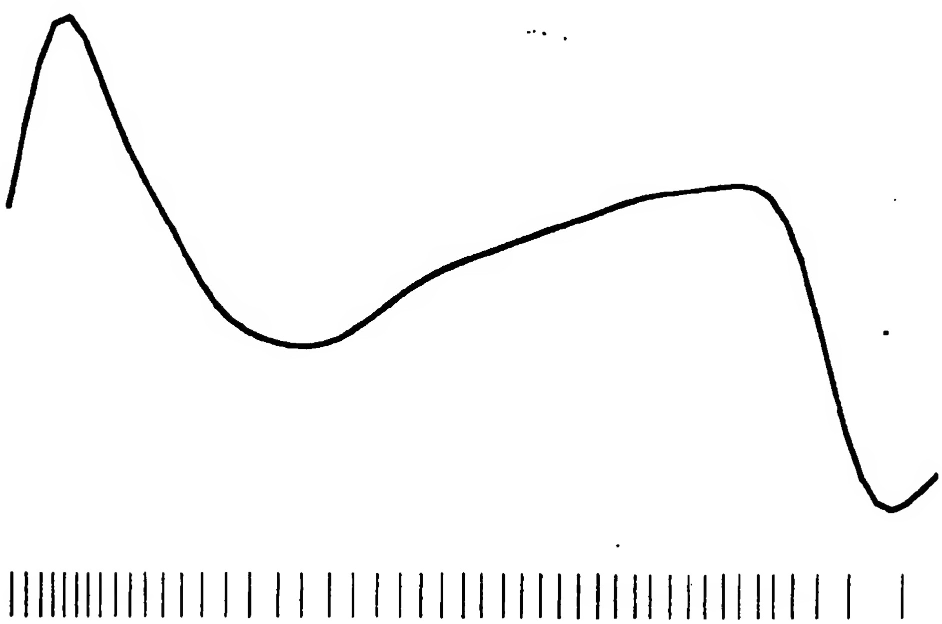


FIG. 12

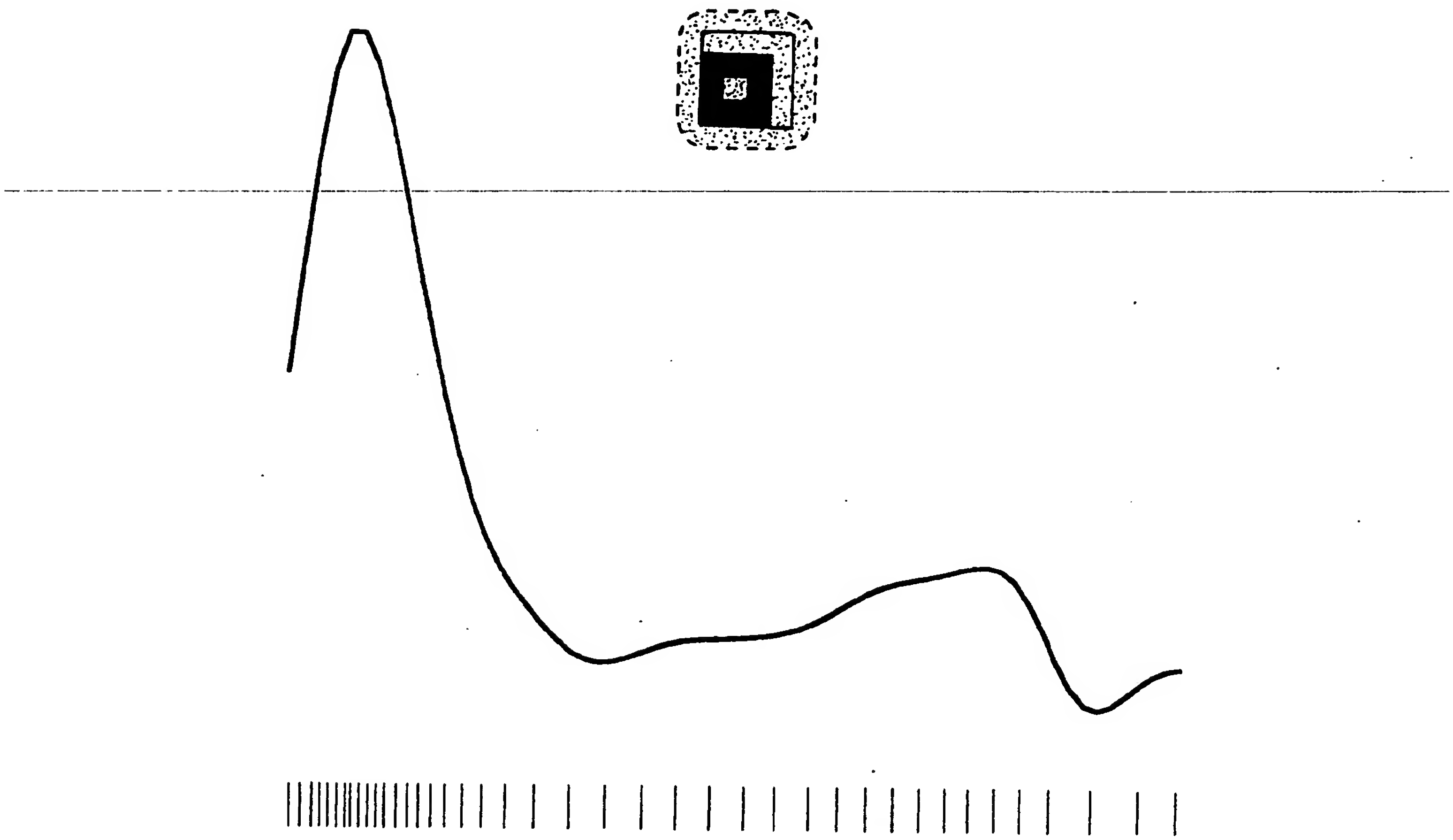


FIG. 13

PCT/US89/03070

International Application No

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [6]

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According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4) A61N 1/00

US CL 128/420.5

II. FIELDS SEARCHED

Minimum Documentation Searched [7]

Classification System	Classification Symbols
US. CL.	128/897, 898, 420.5 623/24, 25

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [9]

Category *	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No. [13]
X	Journal of Neurophysiology, Vol. 57, No. 1, Issued 1987 January (USA), RICHNOMD ET AL, "Temporal Encoding of Two-Dimensional Patterns By Single Units In Primate Inferior Temporal Cortex I. Response Characteristics", see pages 132-146.	1-2
X	Journal of Neurophysiology, Vol. 57, No. 1, Issued 1987 January (USA), RICHMOND ET AL, "Temporal Encoding of Two-Dimensional Patterns By Single Units In Primate Inferior Temporal Cortex II Quantification Of Response Waveform", see pages 147-161.	1-2
X	Journal of Neurophysiology, Vol. 57, No. 1, Issued 1987 January (USA), OPTICAN ET AL, "Temporal Encoding of Two-Dimensional Patterns By Single Units In Primate Inferior Temporal Cortex III Information Theoretic Analysis, see pages 162-178.	1-2

* Special categories of cited documents: [10]

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
30 September 1989	31 OCT 1989
International Searching Authority	**Signature of Authorized Officer**
ISA/US	John Lacyk John Lacyk